SPATIAL LIGHT MODULATOR AND METHOD

BACKGROUND OF THE INVENTION

The invention relates to spatial light modulators, and more particularly to improvements therein which result in low voltage, high speed devices with high contrast ratios.

PLZT (lanthanum modified lead zirconium titanate) is well known for use in spatial light modulators (SLMs), or "light valves". U.S. Pat. No. 5,198,920 by the present inventor gives general background on spatial light modulators. Also see the article "Photoconductive Activated Light Valve for High Definition Projection System", by Garth Gobeli and Thomas Toor, 172/SPIE vol. 1664 High-Resolution Displays and Projection Systems (1992).

FIG. 1 shows a prior art spatial light modulator formed in a relatively thick (e.g., 200 microns) substrate **10** of PLZT. On the top surface **15A** there are formed various positive electrodes, for example, positive electrodes **11** and **13**, and various negative electrodes, such as negative electrodes **12** and **14**, interspaced between the positive electrodes. The opposite voltages applied to the positive and negative electrodes produce "fringing" electric fields **15** between the positive and negative electrodes underneath upper surface **15** of PLZT substrate **10**. The presence or absence of the fringing fields **15** modulate or control the amount of light that can pass through the spatial light modulator or light valve **1**.

A substantial problem of the above prior art of FIG. **1** is that the fringing electric fields **15** are relatively nonuniform. This non-uniformity results in the necessity of applying large voltage differences, usually more than 60 volts, between the positive and negative electrodes in order to achieve the desired level of light modulation. It would be very desirable to be able to use lower electrode voltage differences of less than 60 volts. The non-uniformity of the fringing electric field also means that memory mode material cannot be employed as a substrate.

Very thin layers of PLZT material of thickness in the range from 0.01 to 0.08 microns have been fabricated by depositing PLZT material onto a suitable substrate, using sputtering or liquid phase deposition techniques. Such very thin PLZT films require high activation voltages which lie well to the left of the minimum "A" shown in the curve of "PLZT operating voltage versus PLZT layer thickness" shown in subsequently described FIG. **8**. Also, PLZT substrates with thicknesses in the 100 to 200 micron range have been fabricated by conventional grinding and polishing techniques, but the substrates of this thickness range require very high operating voltages that lie far to the right of the minimum "PLZT operating voltage versus PLZT layer thickness" shown in the curve of FIG. **8**.

There would be a great many applications in the fields of optical computing, optical projectors, and large dynamic range cameras, for a two-dimensional spatial light modulator array in which each spatial light modulator cell operates with voltages less than approximately 60 volts, at operating speeds of more than approximately one million operations per second, and with a contrast ratio of greater than approximately 512 to 1.

Until now, no available or proposed spatial light modulator has been capable of meeting all three of these operating objectives. For example, typical liquid crystal devices (LCDs) operate at low voltages (less than 5 volts) but are quite slow, typically switching at about 30 frames per second, and have a low contrast ratio, typically about 12 to 1.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the invention to provide a spatial light modulator capable of operating at low voltages of less than approximately 60 volts.

It is another object of the invention to provide a spatial light modulator which can be directly driven by silicon LSI or VLSI integrated circuits.

It is another object of the invention to provide a spatial light modulator having high operating speed capability which allows more than approximately one million switching or modulation operations per second.

It is another object of the invention to provide a spatial light modulator having a device contrast ratio which is higher than approximately 512 to 1.

It is another object of the invention to provide a spatial light modulator which has a "modulation depth" that is continuously or nearly continuously attainable, to at least 1 point in 512 so as to have at least 512 distinguishable gray scale contrasts.

It is another object of the invention to provide a spatial light modulator with a layer of solid state electro-optical material having an optimum thickness that results in an optimally low activation voltage.

It is another object of the invention to provide a practical technique for making a layer of PLZT of optimum thickness as to achieve optimally low activation voltage in a spatial light modulator.

Briefly described, and in accordance with one embodiment thereof, the invention provides a spatial light modulator including a thin layer (**10A**) of solid-state electro-optical material having parallel, opposite first (**15A**) and second (**15B**) surfaces, an elongated first electrode (**22**) disposed on the first surface and generally oriented in a first direction, and a plurality of spaced, elongated second electrodes (**23**) disposed on the second surface and generally oriented in a second direction. Regions in the electro-optical material between portions of the first electrode and portions of the second electrodes define pixel regions (**17**) through which light selectively passes in response to differences between control voltages applied to the first electrode and the plurality of second electrodes, respectively. In the described embodiment, the first electrode is of serpentine shape, with "pixel-defining" first portions (B) of the first electrode being oriented in the second direction and second portions (A) of the first electrode located between the first portions being oriented in the first direction, which in one described embodiment is perpendicular to the second direction. The layer of solid-state electro-optical material has a thickness in the range of approximately 5 to 15 microns ((micrometers), and is composed of PLZT. In one embodiment, a plurality of thin regions (**25**) of insulator material are disposed on the first surface between the second portions (A) of the first electrode and the electro-optical material. In one embodiment, the spatial light modulator includes a plurality of the first electrodes (**22**), the first electrodes and the second electrodes defining a rectangular array of pixel regions (**17**).

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a section view diagram of a typical prior art PLZT spatial light modulator.

FIG. **2** is a partial sectional view of a "penetrating field" spatial light modulator of the present invention.

FIG. **3** is a plan view illustrating a one-dimensional spatial light modulator of the present invention.

FIG. 4 is a plan view of a two-dimensional spatial light modulator according to the present invention.

FIG. 4A is a partial section view of the spatial light modulator shown in FIG. 4.

FIG. 5 is a partial section view of a particular type of PLZT spatial light modulator of the present invention using fringing fields in conjunction with transparent electrodes used to modulate the fringing fields by retarding or enhancing them.

FIG. 6 is a diagram of a device that can be used in conjunction with grinding and polishing techniques used to provide thin PLZT layers in accordance with the present invention.

FIG. 6A is a diagram of an interferometric system for measuring the thickness of the PLZT layer being lapped or polished using the device of FIG. 6.

FIG. 6B is a diagram useful in explaining the operation of system of FIG. 6A.

FIG. 7 is a partial section view illustrating a "stacked" or "complex" spatial light modulator having transmission properties which are the combined transmission properties of the stacked individual spatial light modulators.

FIG. 8 is a diagram illustrating a plot of the spatial light modulator operating voltage versus PLZT layer thickness when it is configured as a Kerr cell.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 2 illustrates the basic improvement of the present invention, which includes a PLZT layer that is 5–15 microns thick, which is much more of an optimum thickness than in the most relevant prior art of which the applicant is aware. Obtaining PLZT layers of thicknesses in this range is very problematic because such a thin wafer can not be handled without considerable risk of breakage. However, grinding and polishing techniques can be used in accordance with the present invention to obtain such thin wafers, which then are attached onto a thicker, more rigid, transparent substrate, such as sapphire, indicated by dashed lines 20 in FIG. 2, to provide structural rigidity.

In accordance with the present invention, the thinness of PLZT layer lOA is what allows electrodes to be placed on both the top surface 15A and the bottom surface 15B of PLZT wafer lOA so as to produce effective "penetrating" electrical fields while maintaining inter-electrode spacings sufficiently small that operating voltages do not exceed 60 volts. (Operating voltage is defined as the voltage that when applied to the device will produce a polarization rotation of 90 degrees and consequently will provide the maximum attainable transmission through a Kerr cell.). Specifically, electrodes 22 are located on the top surface of PLZT layer 10A, and negative electrodes 23 are located on the bottom surface. The electrode patterns can be formed by conventional photolithographic processes similar to those used in the semiconductor industry to pattern the various layers on integrated circuits.

As a practical matter, the lower electrodes 23 may be initially patterned on thick substrate 20 before PLZT layer lOA is attached to substrate 20, and the upper electrodes 22 can be patterned on the upper surface 15A after PLZT layer 1OA is affixed to thick substrate 20 and then lapped and polished using the device of FIG. 6 to obtain the desired 5–15 micron thickness of PLZT layer 10A.

In any case, the provision of both upper electrodes 22 and lower electrodes 23 on a thin PLZT substrate of 5–15 micron thickness results in "penetrating" electric fields 15A that extend all the way through the PLZT wafer 10A, instead of "fringing" fields 15 as shown in prior art FIG. 1. The "penetrating" fields 15A are much more uniform than the fringing fields 15 in FIG. 1. Furthermore, the thinness of PLZT layer lOA results in the advantage that the top electrodes 22 and the bottom electrodes 23 can be placed more closely together on the top surface 15A and the bottom surface 15B, respectively. The electrode spacing on a surface of a penetrating field type of spatial light modulator must be fairly close to the thickness of the layer of light medium, i.e., the PLZT layer 10A. Consequently, lower ioltages are required to produce a polarization rotation of 90 degrees and hence the maximum attainable Kerr cell transmission.

For the structure shown in FIG. 2, my computations indicate that with a PLZT layer thickness of 8 microns, upper electrodes 22 are 2 microns wide and spaced 18 microns apart, and bottom electrodes 23 are 2 microns wide and spaced midway "between" pairs of top electrodes 22 as illustrated, for applied "operating voltage" between the (+) electrodes 22 and the (–) electrodes 23 of less than 60 volts to be sufficient to modulate the penetrating fields 15A enough to produce 90 degrees of "rotation" of light passing through PLZT layer 15A. Although I have not yet obtained measurements of the activation or operating voltages of the structure of FIG. 2 with the above-indicated dimensions, I believe, on the basis of both my computations and experiments to date, that whenever I do obtain such measurements, the activation voltage for the optimum PLZT layer thickness may be as low as 30 volts, and perhaps even as low as 15 volts.

FIG. 3 illustrates a "plan view" of a "one-dimensional" arrangement of electrodes 22 and 23 of FIG. 2. The thin PLZT layer 10A is omitted for convenience of illustration, and narrow lines are drawn to indicate the electrodes, which actually have a significant width, as seen in the section view of FIG. 2. In FIG. 3, top conductor 22 extends in a snakelike pattern on the top surface of PLZT wafer 10A, and the various electrodes 23 are formed on the bottom surface 15B of PLZT wafer 10A, and are arranged to "fan out" in the directions on opposite sides of conductor 22. This "fan out" has the advantage of allowing use of conveniently sized and conveniently located contact or bonding pads.

The array shown in FIG. 3 can be made "two-dimensional" as shown in FIGS. 4 and 4A by providing a number of parallel top electrode traces 22-1,2 . . . M that run parallel to but are spaced from each other on the top surface 15A, and by extending the bottom electrodes 23-1,2 . . . N so they are "shared" among the parallel top electrode traces 22.

More specifically, in FIGS. 4 and 4A, a number of generally horizontal serpentine electrodes 22-1,2 . . . M are provided in parallel relationship as shown in FIG. 4 on the top surface 15A of the thin (5–15 microns) PLZT layer 10. On the top surface 15B of thin PLZT layer 10A, a plurality of straight horizontal strips 25-1,2 . . . M of oxide composed of spin-on glass, sputtered SiO_2, or other appropriate insulating layer are provided, so as to partially span the "U" or "inverted U" shaped portions of electrodes 22-1,2 . . . M, respectively. A plurality of vertical metal strips 23-1,2 . . . N are formed on the bottom surface 15B of the thin PLZT layer 10A after the oxide strips 23-1,2 . . . N. The oxide strips 25-1,2 . . . M prevent the "horizontal" portions "A" of electrodes 23-1,2 . . . N from contacting the PLZT material.

The "vertical" portions "B" of electrodes 23-1,2 . . . N define pixel areas or regions 17 of PLZT layer 10A through

which light may pass under control of voltages applied to electrodes 22 and 23, respectively.

The purpose of the oxide strips 25-1, 25-2, . . . 25-M is to provide an insulated region under-lying all of the horizontal portions A of the "snake-shaped" upper electrodes 22-1,2 . . . M This serves the purpose of preventing significant electric fields and associated "cross talk" from occurring between these horizontal portions of the electrode structure and the lower, y-oriented, electrodes. The upper structure thus provides contact to PLZT layer 10A only along the y-oriented portion of its total length. Thus, the oxide strips 25-M and the "snake-shaped" electrodes 22-1,2 . . . M are on the same (top) surface of PLZT layer 10A, with the oxide being deposited first, and with portions of the snake-shaped electrodes 22-1,2 . . . M on the oxide strips 25-1,2 . . . M, respectively. The oxide strip layers, 25-1,2 . . . M in FIG. 4, are deposited onto the top surface of the PLZT. The snake-shaped electrodes, 22-1,2 . . . M are then deposited onto the top surface of PLZT layer 1OA such that the horizontal (x-oriented) segments thereof lay on top of the oxide layers 25-1,2 . . . M, respectively. The only portions of the electrodes 22-1,2 . . . M that contact the PLZT substrate 10A are the vertical (y-oriented) segments. The bottom side electrodes, 23-1,2 . . . N are then deposited so that they are positioned equidistant from adjacent vertical top surface electrode segments.

The only electric fields that penetrate the PLZT layer 10A are between the back surface electrodes and the vertical (y) segments of the top surface electrodes. The electric fields between the horizontal (x-oriented) segments and the back surface electrodes are scre(ened out by the intervening oxide layers.

This set of masks can also be employed to fabricate a one-surface-only spatial light modulator device as follows:

(a) First, the snake-shaped electrode structures 22-1,2 . . . M are deposited. (b) Next, the oxide strips 25-1,2 . . . M are deposited in the positions illustrated so that they overlay the horizontal x-oriented segments of the top surface electrodes 22-1,2 . . . M, respectively. (c) Finally, the y-oriented electrodes 23-1,2 . . . N are deposited onto the same surface of the PLZT layer 10A in the positions illustrated.

This configuration depends on utilizing the fringing electric fields between the electrodes 23-1,2 . . . N and the vertical segments of the initially deposited snake-shaped electrodes 22-1,2 . . . M to activate the spatial light modulator.

In the spatial light modulator shown in FIGS. 3 and 4, the widths of the serpentine top conductors 22-1,2 . . . M might be 2 to 4 microns, and the center-to-center spacing of each SLM cell might be 20 to 25 microns. The width of the bottom electrodes 23 might be 2 to 4 microns.

FIG. 8 shows a graph of PLZT operating voltage applied between the (+) and (−) electrodes as a function of the thickness of the PLZT layer 10A. The PLZT operating voltage is the voltage require to produce a phase change of 90 degrees in the light propagating through the spatial light modulator. There is a minimum at the PLZT layer thickness indicated by "A", because as the thickness of the PLZT layer 10A decreases, the electric field intensity of the "penetrating" electric field produced between the (+) and (−) electrodes increases, increasing the amount of phase shifting. However, there is an opposing effect in that the decreasing thickness of PLZT layer 1OA results in less distance through which the light can propagate, and this tends to decrease the amount of phase shift produced. These opposing phenomena result in an "optimum" thickness.

FIG. 6 indicates how the 5–15 micron thick layers 10A of PLZT material can be produced. For example, a thick piece of PLZT material can be bonded onto a pyrex microscope slide 46 or the like using a suitable epoxy compound. The pyrex slide 46 is then mounted on a moveable piston 34 disposed within a jig or cylinder 36. The position of piston 34 within jig 36 is established by a number of adjustable positioning assemblies each including a stiff compression spring 35 and an adjustment screw 39 (or equivalent mechanical adjustment device) that adjusts the position of piston 34 within jig 36. One end of compression spring 35 exerts a downward force on piston 34. The opposite end of compression spring 35 exerts an upward force against top member 36A of jig 36. Each adjusting screw 39 extends through a corresponding clearance hole 40 in the top member 36A, through a corresponding compression spring 35, into a corresponding threaded hole 41 in piston 34. The enlarged heads of adjusting screws 39 abut the top surface of top member 36A, and act as limit stops to limit the extended lapping or polishing of PLZT layer 10A by lapping/polishing wheel 37. The uniformity of the thickness of PLZT layer 10A can be adjusted by means of adjusting screw 39.

The assembly is used to press the exposed surface of the PLZT layer 10 against the grinding surface of a metallographic lapping wheel 37. A suitable grinding or polishing compound or grit or substance is provided to obtain the desired amounts of grinding or polishing during various phases of the lapping procedure. The adjusting screws 39 are individually adjusted to control the tilt and pressure of the surface of PLZT layer 10A being lapped or polished. When a suitable surface finish is obtained, that surface can be bonded to a suitable substrate, such as a sapphire substrate having "bottom" electrodes 23 already formed thereoni. The opposite face of the sapphire substrate then could be bonded to a suitable pyrex slide, positioned on piston 34, and the lapping/polishing procedure could be repeated until the desired 5–15 micron thickness of the PLZT layer 10 is achieved. Further processing to provide the top electrodes 22 then could be performed.

FIG. 6A schematically illustrates how the amount of adjustment by means of screws 39 in FIG. 6 can be determined to provide the distribution of pressure on the surface of PLZT layer 10A needed to achieve uniform thickness of PLZT layer 10A as lapping or polishing progresses. The entire assembly 36 shown in FIG. 6 can be removed from lapping wheel 37 and positioned in an Michelson interfero;meter set-up 61 including a light source 53, a micrometer-adjustable reference mirror 52, a beam splitter 55 and a compensator 58. Rays such as ray 54 from light source 53 are split by beam splitter 55. Part of ray 54 is reflected as ray 54A to reference mirror 52. Part of ray 54 passes through beam splitter 55 and emerjes as ray 54B. Ray 54B passes through compensating element 58 of thickness and composition identical to beam splitter 55 and emerges as ray 54C. Ray 54C then impinges on the surface of the PLZT layer 10A being polished. Ray 54C is reflected as ray 57A, which passes back through compensator 58 and emerges as ray 57B. Ray 57B is reflected by beam splitter 55 as ray 57C. Ray 54A is reflected by reference mirror 52 as ray 56A, which passes through beam splitter 55 and emerges as ray 56B.

Rays 56B and 57C form an interference pattern which can be observed by a detector or human eye 60. The observed fringe pattern can indicate how uniform the surface being polished of PLZT layer 10A is, how thick it is, and how parallel it is to the upper surface of sapphire substrate 20. Light source 53 is initially a laser source. The adjusting screws 39 of the tilt adjust mechanism (shown as block 36B